WADD TECHNICAL REPORT 60-607

FUNDAMENTAL STUDIES ON THE MECHANISM OF ULTRASONIC WELDING

W. J. Lewis
J. N. Antonevich
R. E. Monroe
P. J. Rieppel

Battelle Memorial Institute

DECEMBER 1960

WRIGHT AIR DEVELOPMENT DIVISION

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BATTELLE MEMORIAL INSTITUTE, Columbus, Ohio
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DECEMBER 1960

Materials Central
Contract No. AF 33(616)-6268
Project No. 7351

WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

This report was prepared by Battelle Memorial Institute under USAF Contract No. AF 33(616)-6266. This contract was initiated under Project No. 7351, "Metallic Materials", Task No. 73516, "Welding and Brazing of Metals", and was administered under the direction of Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division, with Mr. R. E. Bowman serving as supervisor of the project.

This report covers the period of work from March, 1959, to July, 1959. Research was conducted by the Metals Joining Division and the Applied Physics Division of Battelle Memorial Institute. The following individuals contributed to the planning and conduct of the work:

B. W. Conser, Technical Director

D. C. Martin, Consultant, Metals Joining Division

R. D. Buchheit, Assistant Chief, Metallographic Laboratory

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R. E. Pollock, Technician, Metals Joining Division

P. E. McCrady, Technician, Applied Physics Division

ABSTRACT

The fundamental mechanisms of ultrasonic welding and the application of this process to the joining of various heat-resistant materials were investigated.

Previous ~~fundamental~~ studies which had shown the effects of time, temperature, and clamping force on ultrasonic welds were expanded to include studies of the shear force during welding. ~~The results of these studies exhibited considerable scatter, but several trends appeared to be indicated.~~

Ultrasonic spot welds made in various combinations of heat-resistant alloys generally confirmed the results of previous work with these alloys. Cracks were found at the edges of the spot welds in most of the material combinations studied. The effects of these cracks on weldment properties varied with the material. The presence of a reaction zone, apparently consisting of intermetallic compounds, was apparent in ultrasonic welds made between titanium and stainless steel. These findings indicate that ultrasonic welding is not suitable for the production of aircraft-quality spot welds in ~~the~~ heat-resistant and dissimilar metal combinations ~~included in this program~~.

General limitations ~~on the use of this process in its current state of development can be established from the work conducted~~. It is apparent as a material's hardness increases, and the ratio of tensile strength to yield strength decreases, that weldability by the ultrasonic process decreases.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

C. W. Douglass

C. W. DOUGLASS
Chief, Processes & Exploratory
Applications Branch
Applications Laboratory
Materials Central

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FUNDAMENTAL STUDIES ON THE MECHANISM OF ULTRASONIC WELDING

by

W. J. Lewis, J. N. Antonevich, R. E. Monroe,
and P. J. Rieppel

INTRODUCTION

The need for using materials possessing good high-temperature properties for aircraft and space vehicles has been evident for the last decade. One of the difficulties in using these materials is obtaining useful metallurgically bonded joints between dissimilar metals. The use of conventional arc and resistance welding for joining these dissimilar metals has not been satisfactory because of the alloys and intermetallic compounds that form when the metals are melted together. These alloys and intermetallic compounds cause the joints to have very low ductility and poor shock resistance. One method of joining these materials would be cold pressure welding, but the deformation generally required in cold welding is considered a serious drawback. The ultrasonic welding process is considered a pressure-welding method that avoids this drawback and also lends itself to high production rates. If the ultrasonic welding process could be developed to be used in welding heat-resistant metals to themselves and to other metals, some of the difficulties in fabricating structures from these materials would be eliminated. To explore this possibility, a program sponsored by the Wright Air Development Division was conducted at Battelle in 1957 and 1958 to develop procedures for joining similar and dissimilar heat-resistant alloys by ultrasonic welding. This study showed that most metals could be joined by the ultrasonic process but that cracking occurred at the edge of the weld nugget in heat-resistant metals(1)* These results led to the program described in this report to study the fundamental mechanisms of ultrasonic welding and to evaluate the suitability of the ultrasonic process for welding various heat-resisting-metal combinations. It was believed that if the fundamental mechanisms of the process were known, an indication of the suitability and limitations of the process could be determined for welding heat-resistant materials.

Three experimental welding arrangements and several metals with various combinations of mechanical and physical properties were used in efforts to determine the fundamental mechanism of the ultrasonic welding process. Information was obtained on the relationship of shear force and

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*Superscript numbers are references listed at the end of the report.

tip displacement at the onset of welding. The relation of contact area and tip displacement also was determined in these experiments. Analysis of the experimental data and attempts to correlate these data with theoretical analyses of similar systems were largely unsuccessful. However, the information obtained may be useful in understanding the exact mechanism of ultrasonic welding

Spot-welded sheet samples also were studied to evaluate the effect of several material variables on weldability. The effect of material strength, surface cleanliness, and mass on weld properties was determined. Welds in heat-resistant materials also were made as spot-welded sheet samples. However, in welding all of the heat-resistant materials, cracks were obtained at the periphery of the weld nugget.

This report summarizes the results of the fundamental studies and the results of attempts to weld heat-resistant materials.

SUMMARY

Studies were made to develop information related to the mechanism of bonding in ultrasonic welding and to continue the development of welding procedures for use with heat-resistant materials. The fundamental studies included work to establish the shear force during welding and the effects of various material properties on ultrasonic weldability. In some of the fundamental studies, cylindrical or spherical-shaped welding tips were welded to a flat plate. These systems were used because considerable background information was available on the mechanical changes occurring in such systems during the application of loads similar to those encountered in ultrasonic welding. Sheet specimens similar to those used for resistance spot welding were welded to study the weldability of heat-resistant materials and to develop information on the effect of material variables.

Three experimental arrangements were used in these studies to control clamping force between the weld tips and the specimens: (1) a movable anvil in which an air cylinder forced the anvil up to the weld tip, (2) a rigid anvil in which the tip was forced down to the anvil by an air cylinder, and (3) same as (2) except that the force was controlled by a weight on a lever arm. Experimental Arrangement 1 and 2 were used for the cylinder-plate welding setup and Arrangement 3 for the sphere-plate welding setup Experimental Arrangement 2 was used in the welding of sheet specimens.

In studies of the cylinder-plate system, a calibrated magnetic pickup measured the deflection at the anvil in terms of shearing force at the anvil face. Displacement was measured with a capacitance pickup. With this

system, the shear-force measurements were quite erratic. They tended to decrease to a low value after onset of welding. However, in welding iron, the shear force continued to increase at displacements well above those required for onset of welding. The shear-force measurements, because of their inconsistencies, could not be used to evaluate the effects of temperature and material properties on ultrasonic welding. Cracking occurred in welding titanium and nickel with this system.

In studies with the sphere-plate system, a shear-sensitive quartz crystal imbedded in the face of the anvil was used to measure shear forces. Again, the shear-force measurements were quite erratic, and no conclusions could be made on the basis of these measurements.

Studies made with aluminum sheet-specimen weldments and 17-7PH stainless steel sheet-specimen weldments showed the weld shear strength was (1) proportional to the strength of the base material, (2) unaffected by surface cleanliness, and (3) unaffected by mass. Also, weld shear strengths were not lowered in materials (Type 316 stainless steel and Inconel) oxidized before welding at temperatures up to 800 F. The shear strength of Type 316 stainless steel was lowered when it was oxidized above 800 F. The decrease in strength may be due to a change in type and thickness of the oxide that was not readily removed during welding.

In welding the heat-resistant materials, the major defect was cracking at the periphery of the welds. Attempts to eliminate cracking by welding in vacuum and by preheating were not successful. In welds made between titanium and stainless steel, cracks were observed along the bond line and parallel to it rather than at the weld periphery. These cracks were believed due to an alloying or reaction zone that occurred at the weld interface. The hardness of the alloyed zone was very high and the strength of these welds was low, indicating that the alloyed zone was brittle. On the basis of microstructures and hardnesses found in several of the weld zones, it is estimated that the weld zone reached temperatures of about 1500 to 2000 F in the heat-resistant alloys. The heat obtained in this zone is probably generated at the weld interface, so the temperatures at the interface are believed to be near, or at, the melting point of the materials being welded.

The results obtained in this program and in previous work appeared to preclude the use of the ultrasonic welding process for reliable welds of heat-resistant materials for use in aircraft or missile structures. This process could be used in applications where weld cracking of the type observed in this program can be tolerated. However, it is believed that such applications will be limited to simple attachment welds and not for joints required to transmit structural loads. The applicability of the process for welding materials such as aluminum and other relatively soft materials has been demonstrated repeatedly, and it should not be concluded from the above remarks that any serious difficulties exist in this type of application. It may be possible, with further development, to refine the ultrasonic welding

process to the extent required for welding some of the heat-resistant materials. However, the process appears to be extremely sensitive to many variables and precise adjustment and control very likely will be required for such work.

It has been frequently suggested by other investigators that high-output ultrasonic equipment plus high weld-tip force and extremely short welding time may produce crack-free welds in refractory alloys and other materials. The results of this study have not specifically disproved this theory. As stated above, however, the probability of success does not look promising. When high-output transducers are developed for welding, there remains a very serious problem of being able to couple that output to weld pieces without sticking and tearing of surfaces.

At this point, further research to apply this process to refractory and heat-resisting materials is not recommended.

EQUIPMENT AND INSTRUMENTATION

The source of ultrasonic energy in all experimental arrangements used in this investigation was a Model 2400 Sheffield-Cavitron power oscillator with a nickel transducer. The rating of the unit was 2.4 kilowatts at a frequency of 20 kilocycles.

Experimental Arrangement 1

The ultrasonic welding unit described in previous work[1] was used with a modified anvil design (Figure 1). The welding cycle was controlled by two timers. One timer controlled the duration of clamping force. The other timer controlled the duration of the transducer excitation. The welding cycle was activated by a hand switch or foot-pedal switch. The magnitude of clamping force was determined by the air pressure supplied to the air cylinder through a pressure regulator.

Displacement was measured by using a capacitance pickup described previously.[1]

In using Experimental Arrangement 1, it was found results were not consistent. Despite the modified anvil design, wear and damage of bearing surfaces caused the anvil and air cylinder assembly to become compliant with the weld tip. This reduced the transfer of energy to the weld interface and made it impossible to establish fixed conditions of compliance from one weld to the next. Consequently, another welding-unit design was tried.

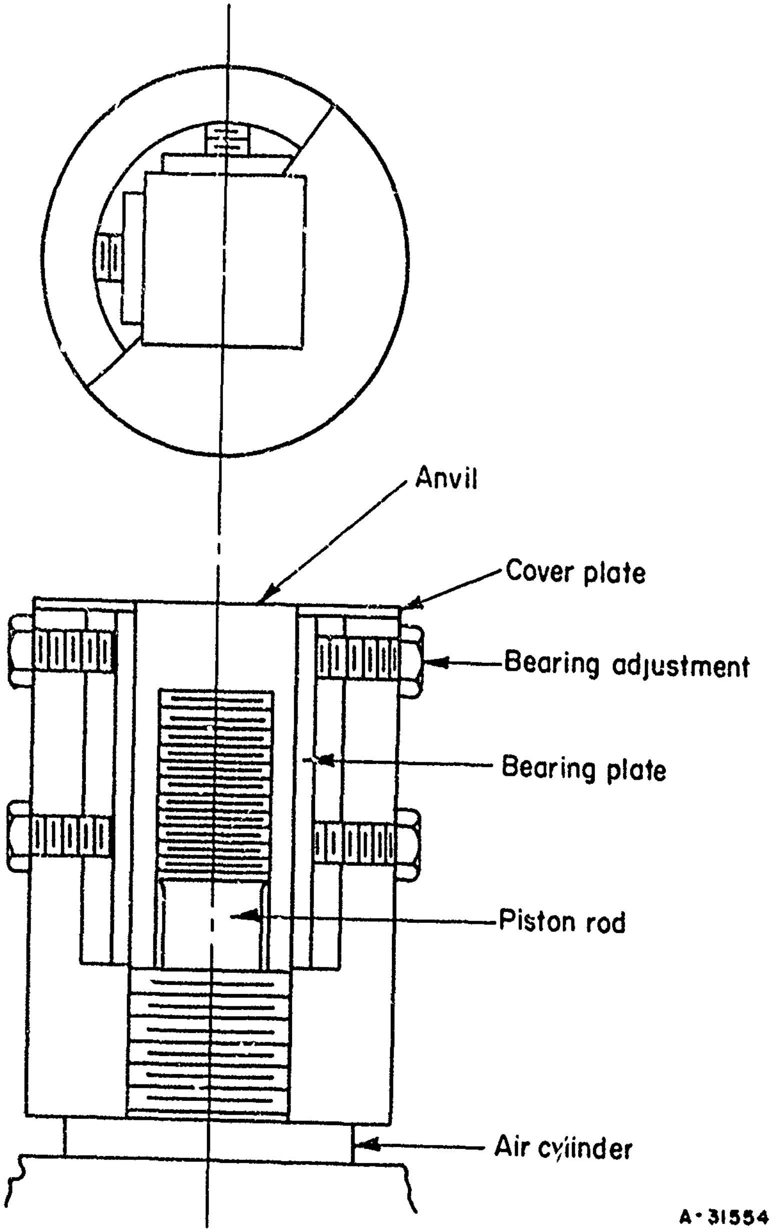


FIGURE 1. ANVIL ASSEMBLY

Experimental Arrangement 2

Figure 2 shows the new design. The transducer assembly was mounted so that it could pivot. Through the lever action of the assembly, the upward force of an air cylinder on the back of the assembly produced a downward force at the welding tip. The anvil was rigidly mounted. Welding conditions were controlled as in the earlier arrangement.

Figure 3 shows the welding tips used with this experimental setup. Figure 4a shows the anvil used for welding sheet samples. It consists of a section of a Sheffield No. 3H204 tool holder to which an interchangeable anvil face is bolted. The anvil face was drilled and tapped so that one or both sheets being welded could be clamped in place to prevent gross movement of the weldment. The replaceable anvil face made it easier to avoid welding between sheets and the anvil by proper choice of anvil material for a given material being welded. In addition, if welding between the anvil and the sample were to occur, the anvil face could be dressed off without grossly disturbing the experimental arrangement.

Figure 4b shows the anvil used with the tip shown in Figure 3b to study relationships between shearing force and displacements during ultrasonic welding in a cylinder-plate system. This anvil was a cantilever beam, and the deflection characteristics of the anvil under transverse loading were determined experimentally. The deflection of the anvil was measured during welding by a calibrated magnetic pickup. This deflection could be related directly to shear force at the anvil face. Sympathetic vibrations in the anvil during welding made it difficult to maintain identical welding conditions from experiment to experiment. Because of this difficulty, a third welding system was used.

Experimental Arrangement 3

Figure 5 shows the third welding arrangement used. It was used in determining relationships between shear force, displacement, and clamping force during ultrasonic welding at a sphere-plate contact.

Figure 6a shows the anvil design with plate specimen in place. The anvil consisted of a Sheffield tool holder No. 3H204 cut so it would not resonate at 20 kilocycles. Figure 6b shows the welding tip with a spherical specimen in place These spherical test specimens were press fit into the tip, which was resonant at 20 kilocycles. A quartz crystal mounted between the anvil face and tool holder was used to measure shear force. The sensing crystal was calibrated against a 1/2-inch cube of Corprene cemented between the weld tip and anvil face. The static stress-strain characteristics of the Corprene were known.

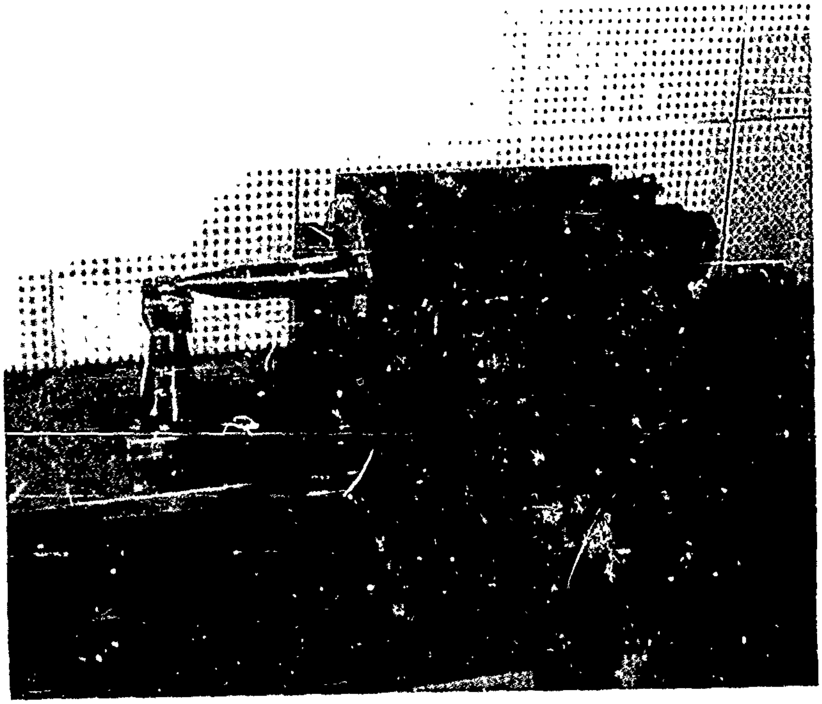
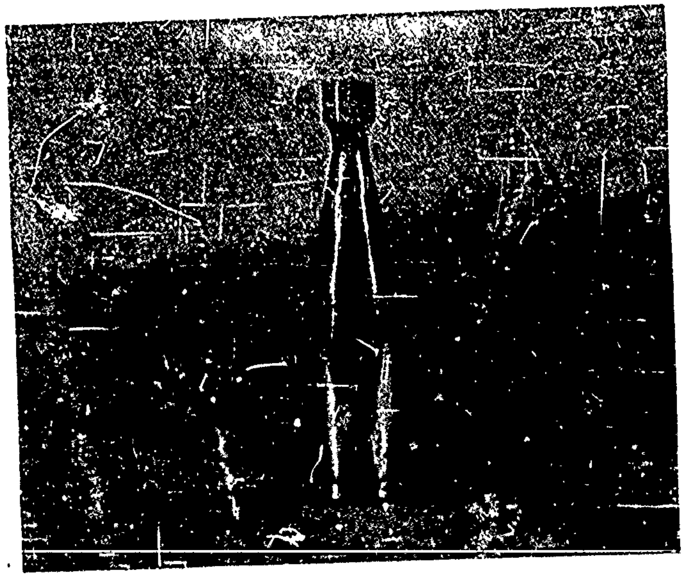
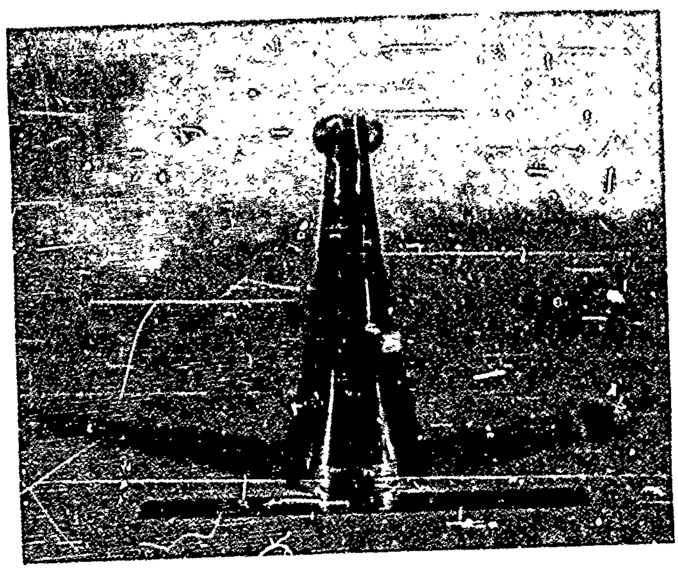


FIGURE 2. WELDER ARRANGEMENT FOR SHEET SAMPLE AND CYLINDER-PLATE WELDING

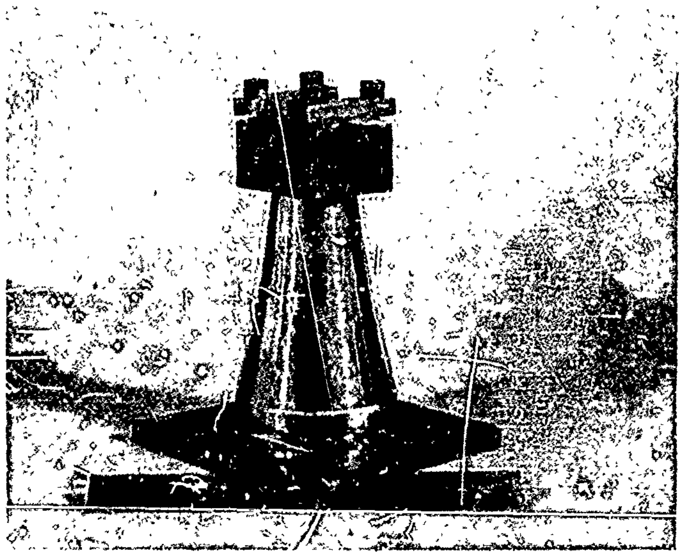


a. Type 7 Used for Tab Welding

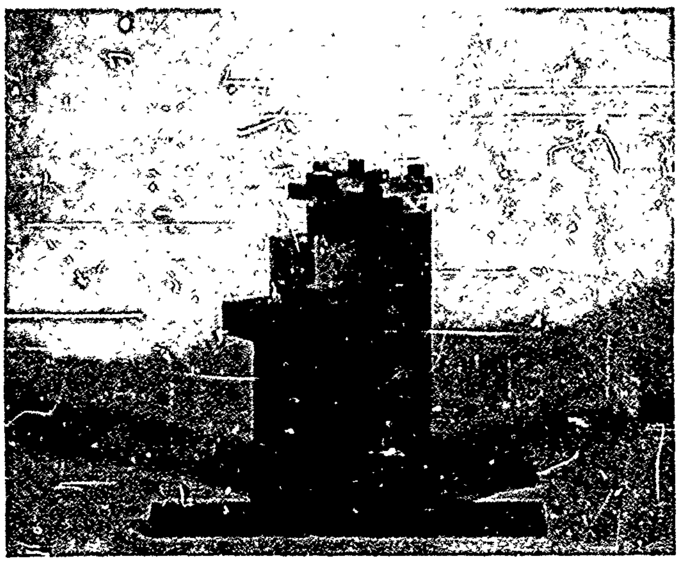


b. Type 8 Used to Study Welding Between Cylinder-Plate Contacts

FIGURE 3. WELDING-TIP DESIGNS



a. For Welding Sheet



b. With Velocity Pickup for Welding Cylinder-Plate Contacts

FIGURE 4. ANVIL DESIGNS

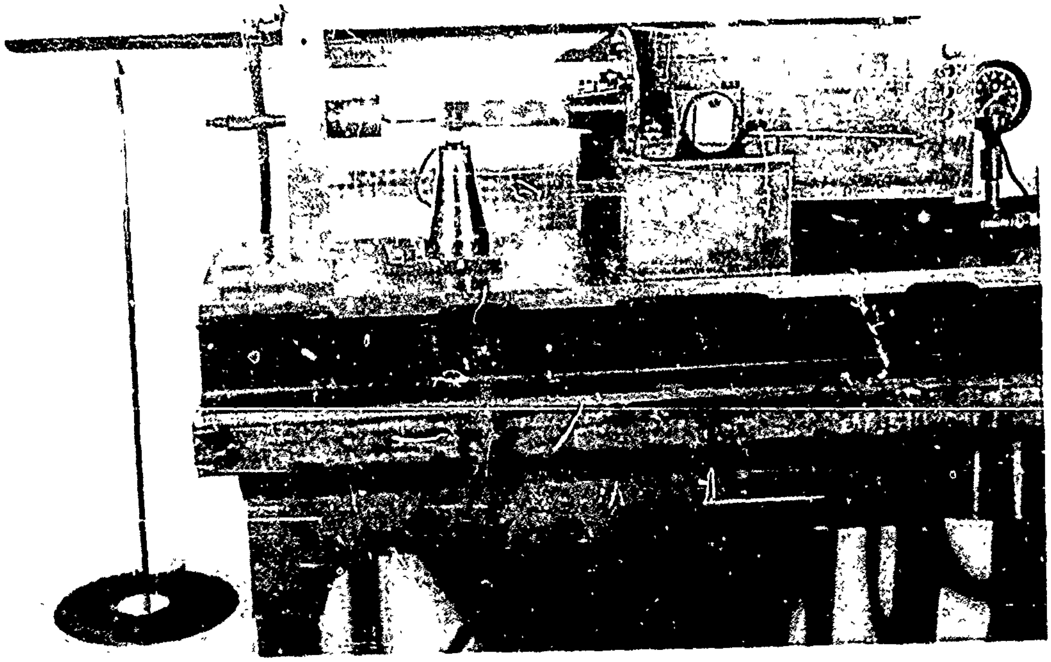
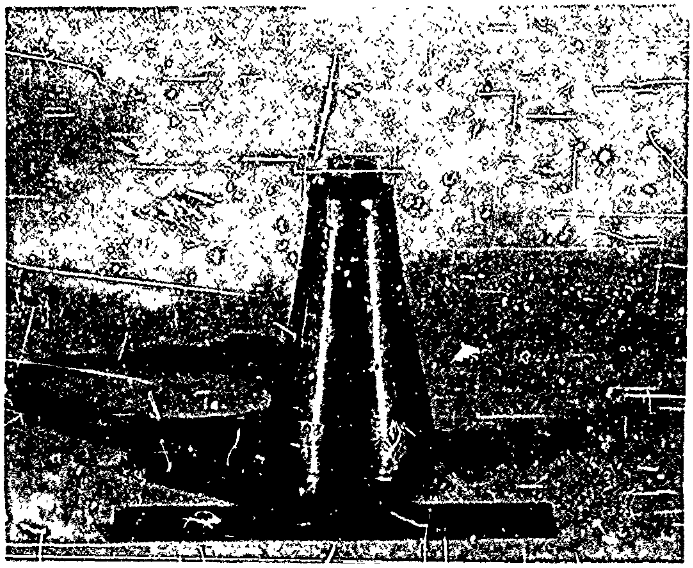
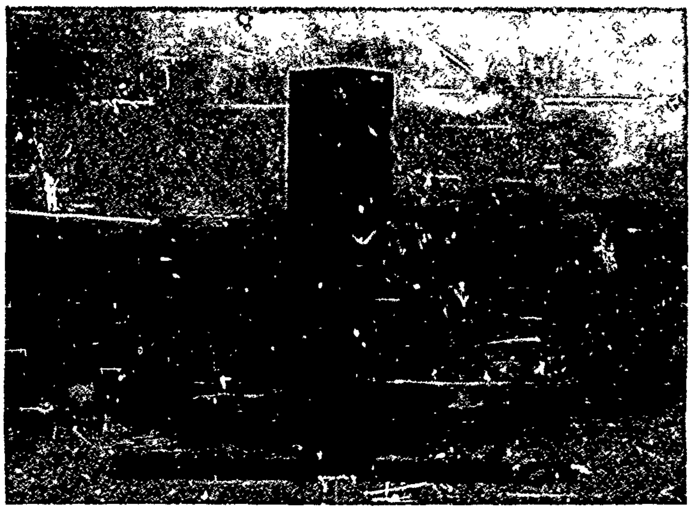


FIGURE 5. WELDER ARRANGEMENT FOR INVESTIGATING WELDS AT SPHERE-PLATE CONTACTS



a. Anvil Assembly



b. Welding Tip

FIGURE 6. ANVIL AND TIP FOR WELDING SPHERE-PLATE CONTACTS

Low clamping forces, low displacements, and low shearing forces were used with this system to avoid overstressing components of the assembly. Clamping force was supplied by a dead-weight loading system. To obtain yield or elastic loading and still not exceed the stress limits of the crystal at the anvil, small-radius specimens were used The test samples were 1/4-inch-radius hemispheres and 1/2 by 1/2 by 1/4-inch plates. The loads used were only large enough to produce shearing forces sufficient to produce welds, yet not large enough to produce sliding between samples and their retaining members.

MATERIALS AND PROCEDURES

The eight sheet materials were used in this program:

(1) 1100-0, 1100-H12, 1100-H14, 1100-H16, and 1100-H18 aluminum

(2) 2024 aluminum

(3) 17-7PH stainless steel

(4) AISI Type 316 stainless steel

(5) C-110M titanium

(6) Niobium

(7) Mo-0.5Ti

(8) Inconel.

The procedures used when working with flat sheet samples were similar to those used in earlier work on ultrasonic welding:

(1) The materials were heat treated, if required for the study.

(2) The materials were degreased and cleaned prior to welding.

(3) The sample to be welded was placed on the anvil, and clamping pressure was applied to clamp the specimen between the tip and anvil.

(4) The ultrasonic energy was applied for a preset time.

(5) A short time after the completion of this cycle, the clamping pressure was released and the weldment was removed.

(6) The weldment was then either broken apart to examine the bond, tested in a tension-shear test, or sectioned for metallographic examinations.

Materials that were heat treated prior to welding were 2024 aluminum and 17-7PH stainless steel.

The 2024 aluminum was received in the solution-treated condition. When required, the 2024 alloy was aged for 9 hours at 325 F. Typical properties of 2024 alloy in these conditions are given below:

	Solution Treated	Aged
Yield strength, 1000 psi	11	50
Ultimate strength, 1000 psi	26	70

The 17-7PH alloy was received in the annealed condition (Condition A). When required, the 17-7PH alloy was conditioned and transformed by heating to 1400 F for 90 minutes, followed by cooling to 60 F within 1 hour (Condition T). The 17-7PH alloy was aged by heating to 1050 F for 90 minutes followed by air cooling to room temperature (Condition TH1050). Typical properties of 17-7PH in these conditions are these:

	Condition A	Condition T	Condition TH1050
Yield strength, 1000 psi	40	100	185
Ultimate strength, 1000 psi	130	145	200

Table 1 summarizes the cleaning procedures used for the materials studied. Tabs 1/2 by 1 inch were used for producing the tension-shear specimens.

The materials used in the fundamental studies (cylinder-plate and sphere-plate systems) are shown in Table 2.

The tip sample was carefully prepared for use before each test. Any roughened surface produced by a previous weld was removed. The plate sample was clamped rigidly to the anvil assembly and a clean surface of the plate sample was used for each test.

After the clamping force was applied, the ultrasonic energy was applied at a selected power setting for 1 second. The tip displacements and shear-force signal were recorded during the welding period.

TABLE 1. CLEANING PROCEDURES

Material to be Welded	Degreasing Agent	Etchant	Etchant Temperature, F	Etching Time, minutes
Aluminum	Acetone	(1) Hot caustic	150-160	1/2
		(2) 50 parts HNO_3 50 parts H_2O	Room	1/2
C-110M	Acetone	25 parts HNO_3 2 parts HF 73 parts H_2O	150	2
17-7PH	Acetone	(1) 50 parts HCL 50 parts H_2O	150	2
		(2) 10 parts HF 7 parts HNO_3 83 parts H_2O	140	1
Mo-0.5 Ti	Acetone	95 parts H_2SO_4 4.5 parts HNO_3 0.5 parts HF 18.8 g/1 Cr_2O_3	120-140	1/2
Niobium	Acetone	90 parts HNO_3 10 parts HF	80	1/2

TABLE 2. MECHANICAL PROPERTIES OF METALS USED IN FUNDAMENTAL STUDIES

Metal	Brinell Hardness Number	Elongation in 2 Inches, per cent	Yield Strength, 1000 psi	Ultimate Strength, 1000 psi	Shear Strength, 1000 psi	Modulus of Elasticity, 10^6 psi
Aluminum (1100)	32.3	20	16	18	11	10
Copper (electrolytic)	77.1	35	30	38	25	16
Iron (Armco)	74.1	47	18.3	41	31	30
Nickel	84.3	50	10	50	52	30
Ti-6Al-4V alloy	279-319	15	136	148	100	15

The surfaces of the tip and the plate were examined for evidence of welding. It was assumed that welding had occurred if metal was plucked from either surface and adhered to the opposite surface. Recorded indications of tip displacement and shear force were transformed to actual values by using the calibration curve.

FUNDAMENTAL STUDIES

Previous work[1] appeared to indicate a general correlation between events occurring during ultrasonic welding and events occurring between surfaces subject to normal frictional loading. Extensive theoretical and experimental studies have been made on friction behavior of sphere-plate and cylinder-plate contacts. The mechanisms associated with motions in a cylinder-plate system subjected to normal and transverse loads have been discussed by Seely and Smith.[2] Similar mechanisms associated with motions in a sphere-plate system have been discussed by several investigators.[3-7] To utilize the information available from research on friction phenomena, experiments were designed to collect information from ultrasonic welds made between either a cylindrical or spherical welding tip and a plate.

Experimental Plan

The results of previous experiments[1] indicate that heating of the faying surfaces of the weld to elevated temperature may be an important factor in producing ultrasonic welds. If so, the temperature reached would be controlled by the energy produced in the weld area during welding. Such heating could promote welding by (1) producing a molten film or (2) producing a soft, plastic zone in the weld area. In either case, intimate metal-to-metal contact could result and welding could then occur. Information available from the research on friction showed that for given welding conditions the energy produced during ultrasonic welding should be directly related to the shear force at the interface.[1,4] If the shear force exerted during ultrasonic welding is known, it should be possible to calculate the minimum energies required for welding various metals. Comparing these with energy values, estimated by the theoretical consideration that the temperature reached is a function of the energy input, the heat capacity, and thermal conductivity of the material being welded, should show whether temperature rise is an important consideration in ultrasonic welding.

Assuming that the melting point of the material being welded is the welding temperature, the minimum energy requirements for welding should

be roughly the same for titanium, nickel, and iron. Aluminum should require only 1/3 this energy, and copper should require 1-1/4 times this energy. If the temperature need only be raised to the recrystallization temperature, to some softening temperature, or to a temperature where diffusion is rapid, the minimum energy required for welding would probably be different, and comparison between the various metals different. However, to calculate energy under nonmelting conditions, the shear force at the weld during welding would still need to be known.

Metals can be pressure welded without heating them. Many of the important factors in pressure welding are related to the mechanical properties of the material involved. In some ways, ultrasonic welding appears to be similar to pressure welding. If welding occurs because of yield at the faying surface, then it should be possible to calculate the stresses present at the onset of welding from measurements of shear force and displacement.

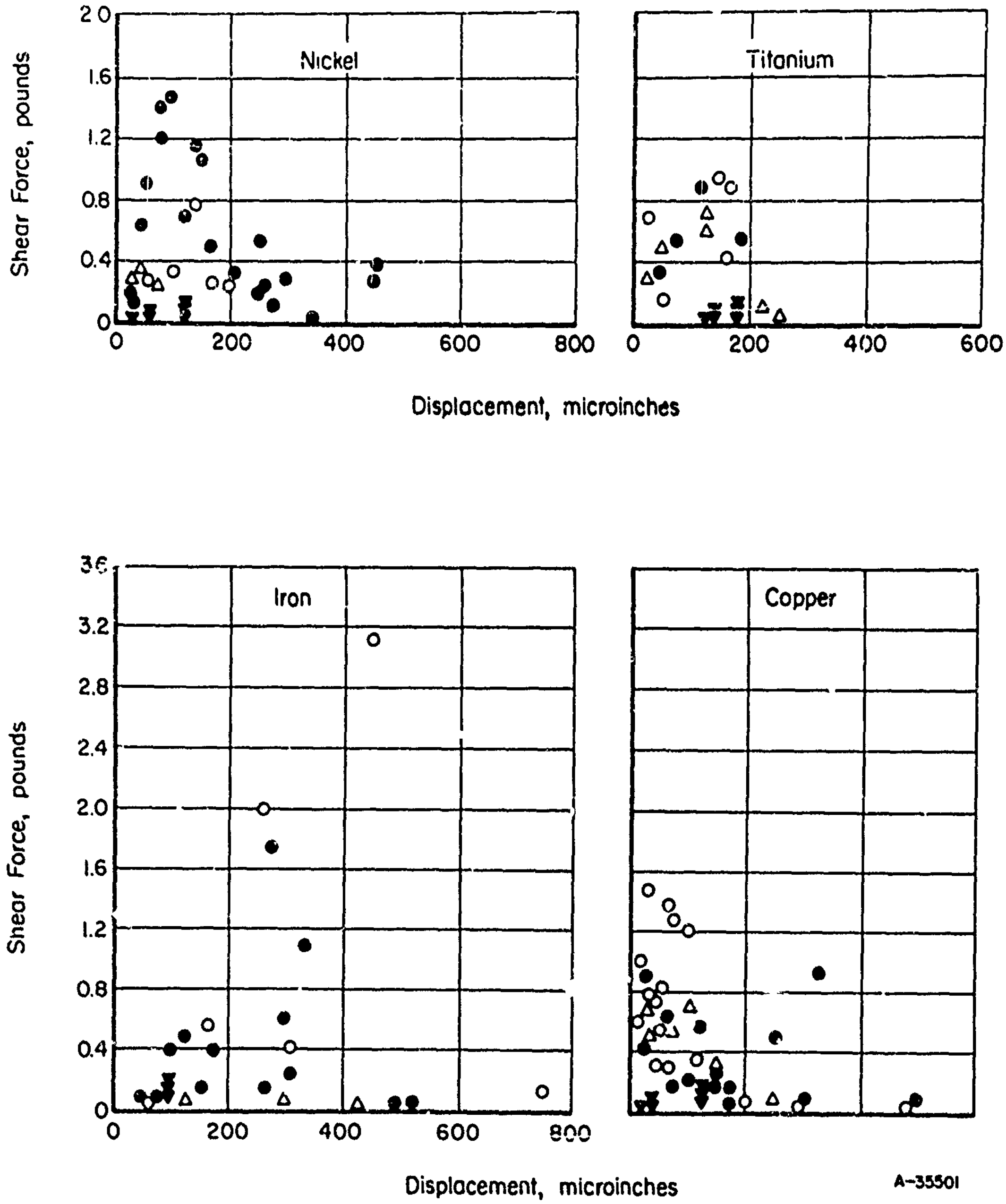
A knowledge of the shear forces present at the weld might also be valuable in arriving at a solution of the problem of cracking in ultrasonic welds. The shear forces could be used to calculate the principal tensile forces in the weld area, at least for a cylinder-plate weld. The magnitude of the principal tensile stress should indicate whether cracking is a matter of overstressing the weld area or is simply a fatigue problem.

Experimental Observations

Cylinder-Plate Welds

Figure 7 shows the relationships between shear force and weld-tip displacement obtained in nickel, titanium, iron, and copper at 50-, 100-, and 200-pound clamping forces. As may be seen, the data vary considerably. This variability is a result of an inability to obtain consistent shear-force measurements. Some trends can be observed as a large number of welding cycles are examined. Apparently, as tip displacements are increased, shear force first increases and then decreases to a low value. For all of the materials examined except iron, the start of welding apparently coincides with the tip displacement at which the shear force began to decrease. For iron, shear force increased for displacements well above those required to produce some welding.

During the examination of test welds, cracks were found in and about the periphery of welds made in titanium when a clamping force of 100 pounds was used. Similar observations were made on nickel samples welded with a clamping force of 50 pounds. Cracks were not observed in welds in copper or iron. There did not appear to be any relationship between the measured shear force and the occurrence of cracking.



Clamping force: △ 50 pounds, ● 100 pounds, ○ 200 pounds.
Displacement at start of welding for clamping force of:
▼ 50 pounds, ▼ 100 pounds, ▼ 200 pounds.

FIGURE 7. RELATIONSHIP OF SHEAR FORCE AND TIP DISPLACEMENT IN CYLINDER-PLATE SYSTEM

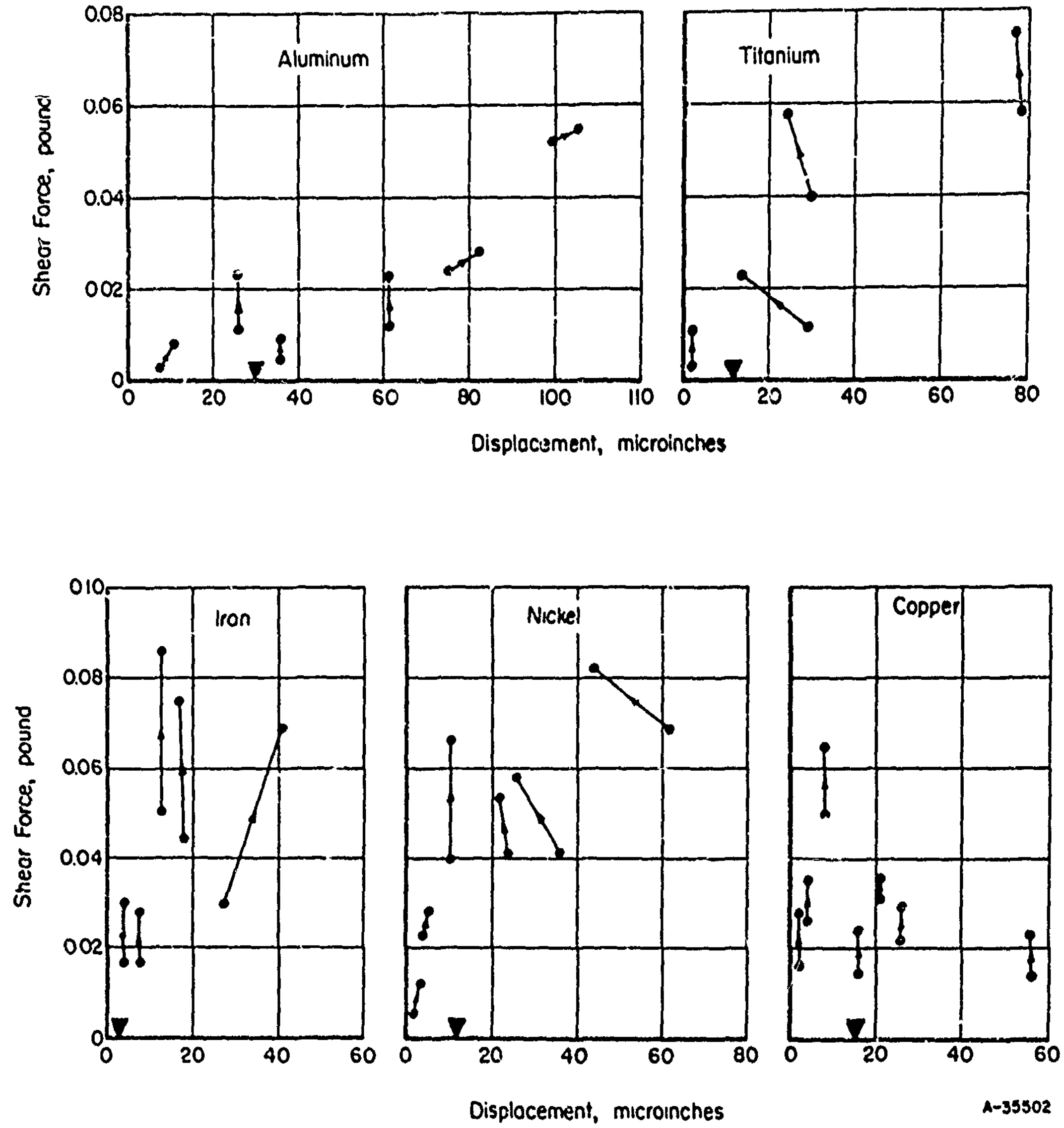
In general, nickel and copper contact areas in test samples were similar, showing progressive abrasion at low displacements and progressive development of welded asperities with increasing displacement until the entire contact area appeared to be welded. These observations were made only on welds made with 50- and 100-pound clamping forces. When 200-pound clamping force was used, instead of abrading, contact areas appeared to be polished at low displacements, with some indication of welding at higher displacement.

Sphere-Plate Welds

Figure 8 shows the relationship of shear force and displacement in the sphere-plate system. Although it had been expected that somewhat more consistent results would be obtained with this arrangement than with previous arrangements, this did not prove to be the case. In fact, the shear-force measurements were more scattered and in addition tended to change during the welding cycle. No consistent behavior was found for the materials used in these experiments. For aluminum, the magnitude of the shear-force measurement seemed to be independent of the onset of welding. For titanium, iron, and nickel, the shear force appeared to increase at the onset of welding. For copper, it appeared to decrease at the onset of welding.

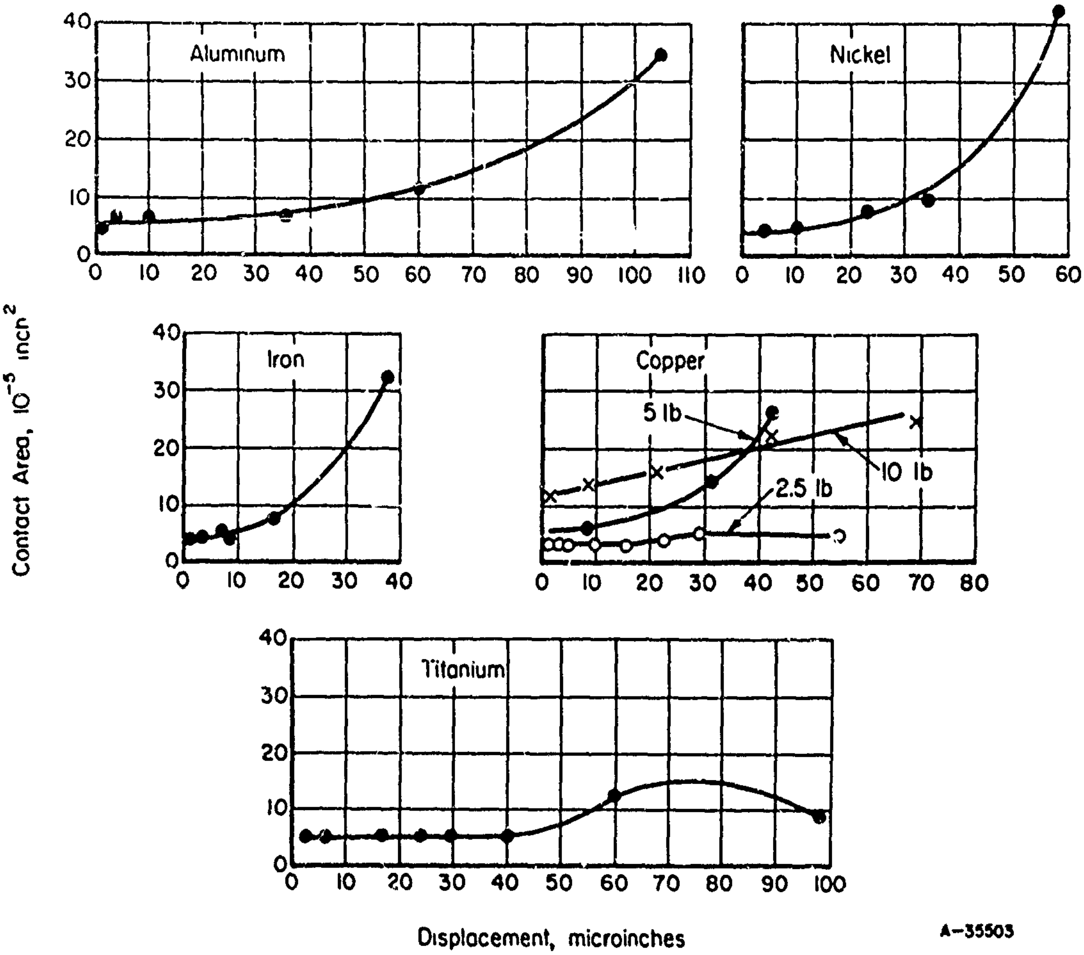
Figure 9 shows the relationship of contact area to tip displacement. The contact area remained constant up to some value of displacement, after which the area increased with further increase in displacement. Microscopic examination of contact areas on the plate specimens showed that the areas at displacements less than those required for the start of welding became progressively more abraded in appearance with increase of displacement. Copper appeared to weld without measurable change of contact area. In all instances, at displacements just short of welding the areas had the appearance of being black, as if covered with oxide particles or fine dust.

Onset of welding seemed to be associated with fretting of the entire contact area and the displacement value at which the contact area started to increase. Welding was found to initiate at contacting asperities, such as those due to machining or scratching of contact surfaces. With increasing displacement, the initial minute asperity welds appeared to grow radially until at relatively high displacement amplitudes they formed a single welded contact area. This observation was not apparent when machining ridges existed on either the hemispherical or plate samples. In these instances, high points on the ridges were found to weld first. These point welds were noted to increase in size with displacement until a line weld area of ridges occurred. Further increases in displacement produced large weld areas that obliterated the initial machining ridges. These weld areas increased in size until the entire contact area appeared to have been welded and surrounded with a ring of oxide or fine black powder.



Clamping force: 2.5 pounds
Displacement at start of welding: ▼

FIGURE 8. RELATIONSHIP OF SHEAR FORCE AND TIP DISPLACEMENT IN SPHERE-PLATE SYSTEM



Clamping force:	2.5 pounds
Tip radius:	1/4 in.
Weld cycle:	1 sec

FIGURE 9. RELATIONSHIP BETWEEN CONTACT AREA AND TIP DISPLACEMENT IN SPHERE-PLATE SYSTEM

Cracks were found only in welds in titanium when normal welding conditions were used. These cracks were normal to the direction of motion and tangential to the leading or trailing edge of the contact area. However, cracks and pulled nuggets covered with black oxide and debris occurred in all five metals when weld cycles were prolonged or displacements were exceptionally high.

Discussion of Fundamental Studies

Previously, it was pointed out that a knowledge of the shear force generated at the weld area should permit evaluation of the role of temperature rise at the faying surface of the weld and of the role of the mechanical properties of the materials being welded. Three different experimental techniques were used to try to measure the shear forces at the weld area. The results obtained do not appear to be consistent enough to be used for a fundamental evaluation of the effects of temperature and mechanical properties. Calculations on the basis of the melting point, specific heat, and thermal conductivity of each material indicate that about the same energy should be required to produce welds in titanium, nickel, and iron. Similar calculations indicate about 1/3 of this energy would be required for welding aluminum and about 1-1/4 times this energy for copper. A consideration of the shear-force measurements made by using the cylinder-plate experimental setup shows that these measurements do not rank the energy requirement this way. Remembering that the energy input to the weld is proportional to the shear force and using the maximum shear force prior to onset of welding as the criterion, the metals tested would be rated as follows:

(1) Nickel and copper would require the highest energy input.

(2) Titanium would require about 1/2 this amount.

(3) Iron, if the unexplained increase in shear force after onset of welding is ignored, would require the least energy input.

Consequently, it appears that the shear-force measurements are in error.

The same can be said for the measurements made with the sphere-plate experimental setup. The only consistent measurements are the contact area measurements. When contact-area and shear-force measurements are considered together, an order of energy inputs is obtained that is entirely different than that developed by considering the heat capacities and thermal conductivities of the materials.

Attempts to use the shear-force measurements to obtain meaningful evaluation of the role material properties play in ultrasonic welding were not successful.

It was not possible to use the shear-force measurements to determine whether the basic assumptions which were discussed previously are right or wrong. Experimental proof of their validity must be sought by other means.

Sheet Spot-Weld Studies

The effects of several material variables on properties of ultrasonic welds were studied with sheet samples. Two sheets of material were welded together to make tension-shear samples similar to those used in resistance spot welding. These studies were made to determine the effects of selected mechanical properties, surface conditions, and material configurations on the properties of an ultrasonic weld.

Effects of Cold Work

Ultrasonic welds were made in 0.04-inch-thick 1100-0, 1100-H12, 1100-H14, 1100-H16, and 1100-H18 aluminum to study the effects of cold work on weldability. The welds were made by using Experimental Arrangement 1. Welding conditions were selected on the basis of preliminary studies and on previous work.[1] In the preliminary studies, welds were made under a variety of welding conditions. The welds were evaluated by tearing them apart manually. Welding conditions were varied until either the welds could not be torn apart or nuggets were pulled. A 100-pound clamping force and a 5-second welding time were selected in welding tension-shear specimens of these materials. Power settings were used that supplied about 1.2 kw to the transducer. The welds in 1100-H14 and 1100-H18 were tested in the as-welded condition and after postweld annealing.

The effect of cold work on the strength of the welds is shown in Figure 10. The data show that weld strength increases in the as-welded condition with degree of cold work. Similar behavior was noted in previous work. In the postweld-annealed condition, the weld strengths of the cold-worked aluminum were similar to those of the 1100-0 aluminum in the as-welded condition. However, the annealed welds failed in the base metal, and the nugget size of these welds was less than the nugget size of the welds in the 1100-0 aluminum. This indicates that the weld strengths reflect the tensile strength of the base metal, and the strength of welds annealed after welding was greater per unit area than welds made in annealed material.

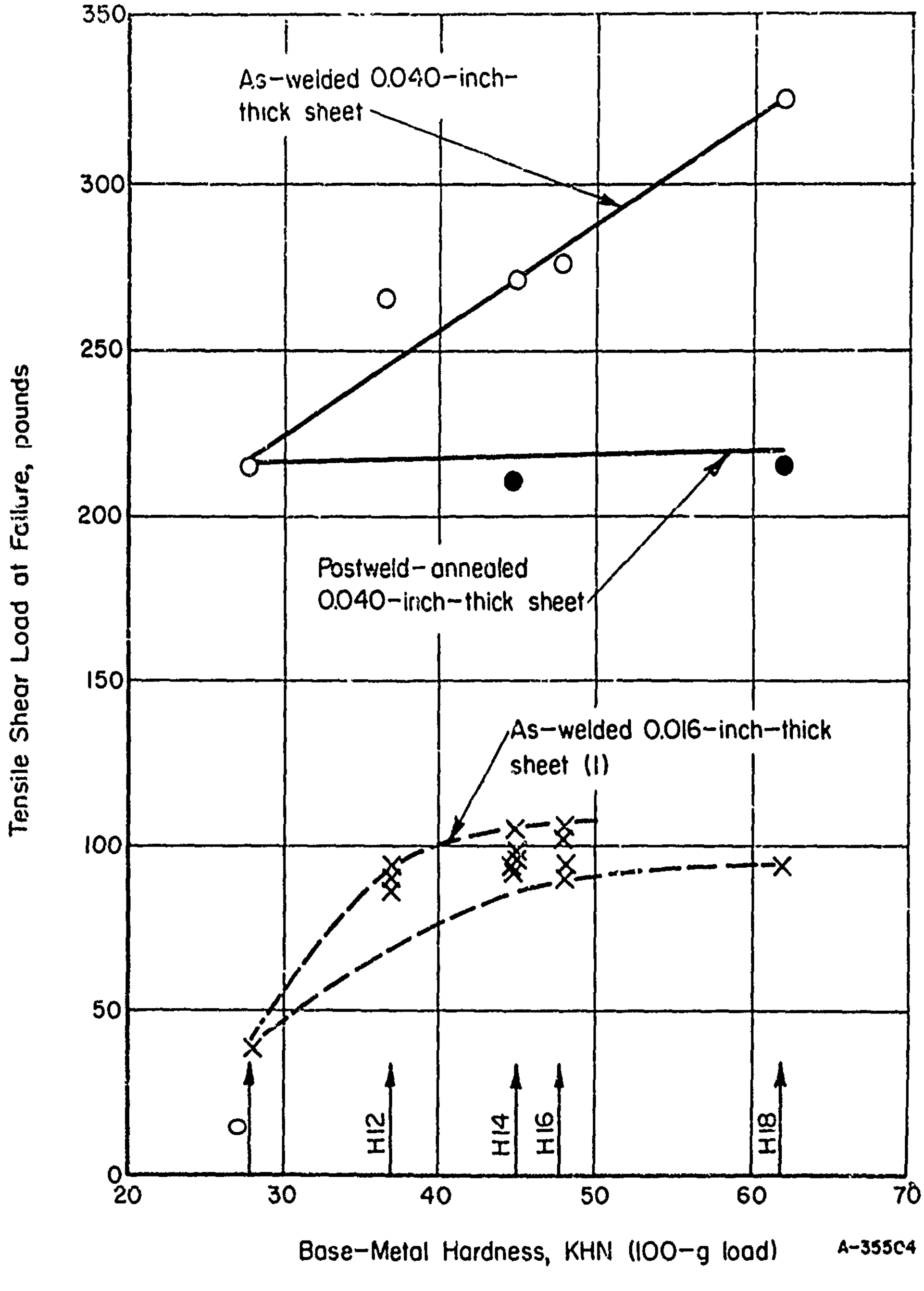


FIGURE 10. EFFECT OF COLD WORK ON TENSILE SHEAR STRENGTH OF 1100 ALUMINUM

Effect of Yield Strength and Tensile Strength

Ultrasonic welds were made in 0.016-inch-thick 2024 aluminum and 0.015-inch-thick 17-7PH stainless steel to study the effects of yield and tensile strengths on weldability. Welds were made in material solution treated or conditioned and transformed before welding (relatively low yield strength) and aged after welding for comparison with welds in material that had been both solution treated or conditioned and transformed and aged before welding (relatively high yield strength). Welds also were made in mill-annealed 17-7PH material. All of the welds were made with a Type 7 Monel tip and an anvil that was coated with a hard-facing alloy. These welds and all succeeding welds were made using Experimental Arrangement 2.

The 2024 aluminum was welded with an estimated power input of 1.4 kw to the transducer and the 17-7PH was welded with an estimated power input of 2.2 kw to the transducer. The specimens were clamped to the anvil during welding. In welding these materials, it was found that excessive tip sticking occurred; in addition, excessive sticking to the anvil occurred during welding 2024 aluminum.

The shear strengths of welds in 2024 aluminum (Table 3) and 17-7PH stainless steel (Table 4) showed the same trends. That is, most of the welded specimens failed in the base metal at the edge of the weld nugget, and the weld strengths reflected only the strength of the base metal. Figure 11 shows the relationship of base-metal hardness and weld strength. The data indicate that the tensile strength did not affect weldability of these materials.

Welds made in 2024 aluminum and 17-7PH stainless steel also were examined metallographically. It was found that sound bonds were obtained in the welds made in 2024 aluminum. Welds made in this material in the solution-treated condition did not contain cracks. However, gross cracking was observed in material welded in the aged condition and in material welded in the solution-treated condition and aged after welding. Cracks were found that ran parallel to the bond line. The cause of these cracks is not known. However, cracking was observed only in 2024 aluminum that was aged either before or after welding, so the cracking may have been influenced by the aging treatment used.

Sound bonds also were obtained in joints in 17-7PH stainless steel. However, small cracks were found in the welds at the edge of the nugget. The cracks were found in 17-7PH sheet in all conditions. Examples of cracking in 17-7PH and tip and anvil sticking are shown in Figure 12 It also can be seen in the figures that a change in microstructure occurred in the nugget area, especially in the material heat treated before welding. The change in microstructure is due to heating and straining from ultrasonic motion that occurs in making these welds. Knoop hardnesses of the welds and

TABLE 3. TENSILE SHEAR STRENGTH OF ULTRASONIC WELDS IN 0.016-INCH-THICK 2024 ALUMINUM

Clamping Force, pounds	Welding Time, seconds	Welded and Tested in the Solution-Treated Condition: Shear Strength, pounds	Welded and Tested in the Solution-Treated Condition: Type of Failure	Welded and Tested in the Aged Condition: Shear Strength, pounds	Welded and Tested in the Aged Condition: Type of Failure	Welded in the Solution-Treated Condition, Tested in the Aged Condition: Shear Strength, pounds	Welded in the Solution-Treated Condition, Tested in the Aged Condition: Type of Failure
200	0.5	195	Shear	255	Base metal	390	Base metal
200	1.0	282	Shear	375	Base metal	370	Base metal
200	2.0	220	Shear	390[a]	Base metal	420	Base metal
250	0.5	275	Shear	180	Shear	380	Base metal
250	1.0	315	Base metal	360[a]	Base metal	425[a]	Base metal
250	2.0	305[a]	Base metal	360[a]	Base metal	420	Base metal
300	0.5	295	Base metal	270	Base metal	210	Shear
300	1.0	305	Shear	395	Base metal	435	Base metal
300	1.0	310[a]	Base metal	360[a]	Base metal	410	Base metal

(a) Failures occurred in base metal away from the weld nugget. All other base-metal failures initiated at the edge of the nugget.

TABLE 4. TENSILE SHEAR STRENGTH OF WELD IN 0.015-INCH-THICK 17-7PH STAINLESS STEEL

Welding Conditions	Welded and Tested in Condition T: Shear Strength, pounds	Welded and Tested in Condition T: Type of Failure[a]	Welded and Tested in Condition TH1050: Shear Strength, pounds	Welded and Tested in Condition TH1050: Type of Failure	Welded in Condition T, Tested in Condition TH1050: Shear Strength, pounds	Welded in Condition T, Tested in Condition TH1050: Type of Failure
250-pound clamping force, 1-second welding time	640	POB	665	POB	760	POB
	505	Shear	660	POB	600	POB
	530	Base metal	665	POB	615	POB
	585	Base metal	620	POB	625	POB
	505	Base metal	680	POB	635	POB
Average	553		659		635	

(a) POB = pulled-out button; base-metal failures occurred at edge of nugget.

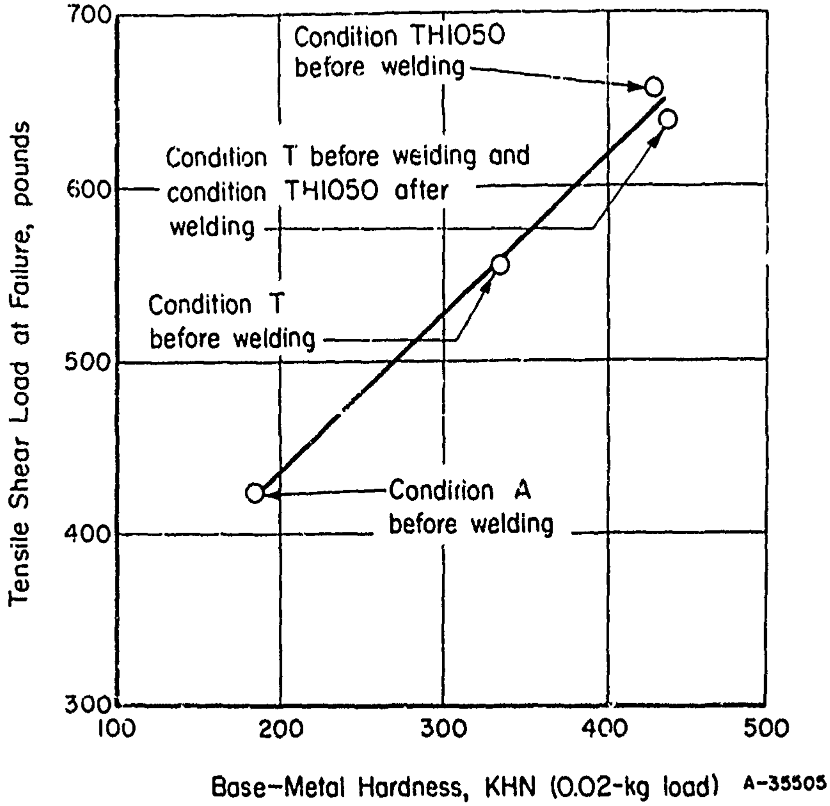
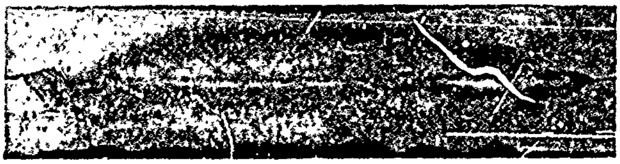


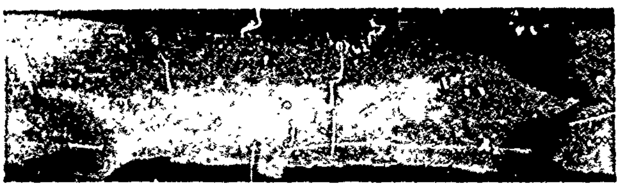
FIGURE 11. RELATIONSHIP OF BASE-METAL HARDNESS AND TENSILE SHEAR STRENGTH OF WELDS IN 0.015-INCH-THICK 17-7PH STAINLESS STEEL

Welded in Condition A

Welded in Condition T



Welded in Condition T, Aged After
Welding, Condition TH1050



Welded in Condition TH1050

30X Etchant: 80 Glycerine, 5 grams $FeCl_3$, 20 HCl, 5 HNO_3 N67779

FIGURE 12. CROSS SECTIONS OF ULTRASONIC WELDS IN 17-7PH STAINLESS STEEL

Welding conditions:	Clamping force:	250 pounds
	Weld time:	1 second
	Power to transducer:	approximately 2.2 kw.

base metals are shown in Table 5. The data show that the hardness of the weld nugget is lower than that of the base metal except in the welds made in annealed sheet (Condition A). Hardness of all of the welds is considerably lower than that of the conditioned and transformed (Condition T) base metal. The conditioning was at 1400 F and, on the basis of the hardness data, the weld area was heated to temperatures much higher than 1400 F. It is estimated that the nugget areas were heated to about 1800 F in welding, and the weld interface was heated to much higher temperatures than 1800 F.

TABLE 5. AVERAGE HARDNESS VALUES OBTAINED IN WELDS IN 0.015-INCH-THICK 17-7PH STAINLESS STEEL

Condition of 17-7PH	Knoop Hardness Numbers, 0.2-Kg Load	
	Base Metal	Weld Area
Annealed (A)	185	219
Conditioned and transformed (T)	346	231
Conditioned and transformed before welding and aged after welding (TH1050)	437	261
Conditioned and transformed and aged before welding (TH1050)	429	244

Attempts were made to eliminate cracking in 17-7PH stainless steel by welding in a vacuum with and without preheat. This was done because it is known that fatigue properties of metals are usually higher in vacuum than in air[8] and if the cracking is due to fatigue, it might be eliminated. Preheating was used to soften the weld area. Welds were made while using the same power settings as those used to weld 17-7PH in air. The weld anvil and tip were enclosed in a chamber that was evacuated to 5 microns for welding. Preheat was obtained by connecting three low-voltage transformers in series to the anvil and tip; temperatures of about 800 F were obtained in the weld zone.

The shear strengths of the welds in 17-7PH are shown in Table 6. The data show that weld strength was not improved by the use of vacuum or vacuum plus preheat. As would be expected, the welds made in vacuum were much cleaner than those made in air. That is, the debris that accumulates around the weld nugget is colored by oxidation in welds made in air, but not in welds made in vacuum.

Metallographic examinations of the welds revealed that those made in air had the best bond quality, but all contained cracks. The welds made in vacuum had the poorest bond quality but had fewer cracks than welds made in air or in vacuum with preheat. In several of the welds made in vacuum,

cracks were not observed. The poor bond quality of welds made in vacuum may be due to the increase in coefficient of friction or shear forces of rubbing surfaces in vacuum, which would result in lower displacements. This also may account for the decrease in cracking obtained in welds made in vacuum.

TABLE 6. TENSILE SHEAR STRENGTH OF ULTRASONIC WELDS IN ANNEALED 0.015-INCH-THICK 17-7PH STAINLESS STEEL

Clamping Force, pounds	Welding Time, seconds	Welded in Air		Welded in Vacuum		Welded in Vacuum Plus 800 F Preheat	
		Shear Strength, pounds	Type of Failure[a]	Shear Strength, pounds	Type of Failure[a]	Shear Strength, pounds	Type of Failure[a]
200	0.5	410	Shear	370	POB	330	Shear
200	1.0	465	POB	515	POB	445	Shear
200	1.5	385	POB	450	POB	460	POB
200	2.0	--	--	505	POB	470	POB
250	0.5	425	POB	280	Shear	385	Shear
250	1.0	540	POB	335	Shear	470	Shear
250	1.5	430	POB	435	POB	485	POB
250	2.0	--	--	400	Shear	535	POB
300	0.5	380	Shear	350	Shear	360	Shear
300	1.0	420	Shear	430	POB	460	POB
300	1.5	450	Shear	425	POB	420	Shear
300	2.0	--	--	440	POB	355	Shear

(a) POB = pulled-out button.

Effect of Surface Cleanliness

Welds were made in 0.015-inch-thick annealed 17-7PH stainless steel to determine the effect of surface cleanliness on weldability. Welding procedures were the same as those described previously for welding 17-7PH stainless steel. The sheet was welded in the following conditions: (1) as received, (2) degreased, (3) degreased and pickled, (4) oil on the interface, and (5) grease on the interface. Shear strengths of welds made in these sheets are shown in Table 7. The data show that weld shear strength was not affected by cleanliness. Apparently, any films or foreign material on the interface are removed in the initial excursions of the welding cycle.

Ultrasonic welds also were made to determine the effects of oxide films on the strength of welds. The welds were made in 0.018-inch-thick Inconel sheet and 0.016-inch-thick Type 316 stainless steel sheet that had been exposed at 100, 200, 400, 600, 800, and 1000 F for 15 minutes in air. It is likely that the oxide thickness and type would vary in the specimens over this temperature range.

TABLE 7. THE EFFECT OF SURFACE CLEANLINESS ON THE TENSILE SHEAR STRENGTH OF ULTRASONIC WELDS IN 0.015-INCH-THICK ANNEALED 17-7PH STAINLESS STEEL

Welding Condition	As Received		Degreased		Degreased and Pickled		Oil on Interface		Grease on Interface	
	Shear Strength, pounds	Type of Failure(a)	Shear Strength, pounds	Type of Failure(a)	Shear Strength, pounds	Type of Failure(a)	Shear Strength, pounds	Type of Failure(a)	Shear Strength, pounds	Type of Failure(a)
250-pound clamping force, 1-second welding time, approximately 2.2 kw to transducer	360	Shear	455	POB	425	POB	420	Shear	430	POB
	415	POB	395	POB	375	Shear	430	POB	440	POB
	420	POB	440	POB	400	POB	405	Shear	410	POB
	405	POB	410	Shear	340	Shear	405	PCB	430	POB
Average	400		425		385		415		427	

(a) POB = pulled-out button.

The shear strengths of the welds are shown in Table 8. The strength of welds was not affected significantly by sheet oxidized at temperatures up to 800 F. The strength of welds made in AISI Type 316 stainless steel exposed at temperatures of 1000 F decreased, indicating that the oxide thickness or type obtained at this temperature affected weldability. The strength of welds made in Inconel was erratic, and definite conclusions could not be drawn.

Effect of Sheet Mass on Weld Strength

Welds were made to determine the effect of sheet mass on weld strength. This was done to see if ultrasonic energy was dissipated because of the increase in size. The welds were made in 0.040-inch-thick 1100-H18 aluminum. The sheet mass was varied from 0.004 to 0.024 pound. Welds in all sheets were made as easily as welds in the standard size specimens.

The shear strengths of welds are shown in Figure 13. It can be seen that weld strength was not affected by the change in mass.

Multiple Spot Welds

Multiple ultrasonic welds were made in 0.040-inch-thick 1100-H18 aluminum, simulating seam welding. The purpose was to determine the effect of succeeding welds on the initial welds. The welds were made about 1/2 inch apart, and as many as 10 spots were made per sheet. No difficulties were found in making the welds. The initial welds did not fracture or appear to be affected in any way by the succeeding welds.

Discussion of Sheet Spot-Weld Studies

The data obtained from welding studies on sheet samples showed that weld strength increased with yield and tensile strength. This was found both in 1100 aluminum cold worked to different strength levels and 2024 aluminum and 17-7PH stainless steel heat treated to different strength levels. In welding these materials, weld shear strength was proportional to base-metal hardness or tensile strength.

Weldability of 17-7PH stainless steel was not affected by surface cleanliness. The properties of welds in material coated with grease and oil were similar properties to those of welds in material cleaned thoroughly. However, weld strengths of Type 316 stainless steel were lowered if the sheet materials were exposed to oxidizing atmospheres at temperatures above 800 F before welding. Weld properties were not lowered in sheet oxidized at temperatures below 800 F.

TABLE 8. TENSILE SHEAR STRENGTHS OF ULTRASONIC WELDS IN INCONEL AND TYPE 316 STAINLESS STEEL

Welding Conditions	Tensile Shear Strength, pounds, and Type of Failures of Welds in Sheet Exposed for 15 Minutes in Air at Indicated Temperature											
	100 F		200 F		400 F		600 F		800 F		1000 F	
	Shear Strength	Type of Failure(a)	Shear Strength	Type of Failure(a)	Shear Strength	Type of Failure(a)	Shear Strength	Type of Failure(a)	Shear Strength	Type of Failure(a)	Shear Strength	Type of Failure(a)
						0.018-Inch-Thick Inconel						
250-pound clamping force, 1-second welding time, approximately 2.2 kw to transducer	470	POB	440	POB	405	POB	500	Base metal	420	Shear	335	Shear
	480	Base metal	345	POB	375	Shear	545	Base metal	445	Shear	325	POB
	410	POB	460	POB	455	Base metal	490	Base metal	420	Shear	380	Shear
	525	Shear	450	POB	435	POB	450	Base metal	525	POB	450	Shear
Average	471		419		417		529		452		372	
						0.016-Inch-Thick Type 316 Stainless Steel						
250-pound clamping force, 1-second welding time, approximately 2.2 kw to transducer	400	POB	510	POB	520	Base metal	540	POB	500	Shear	370	Shear
	520	Base metal	505	Base metal	465	Base metal	485	Base metal	535	POB	350	Shear
	545	Base metal	525	Base metal	505	Base metal	510	POB	545	Base metal	380	Shear
	495	Shear	515	Base metal	470	Base metal	485	Base metal	350	Base metal	390	POB
Average	490		513		490		505		482		372	

(a) POB = pulled-out button.
Base metal = fracture occurred at edge of nugget.

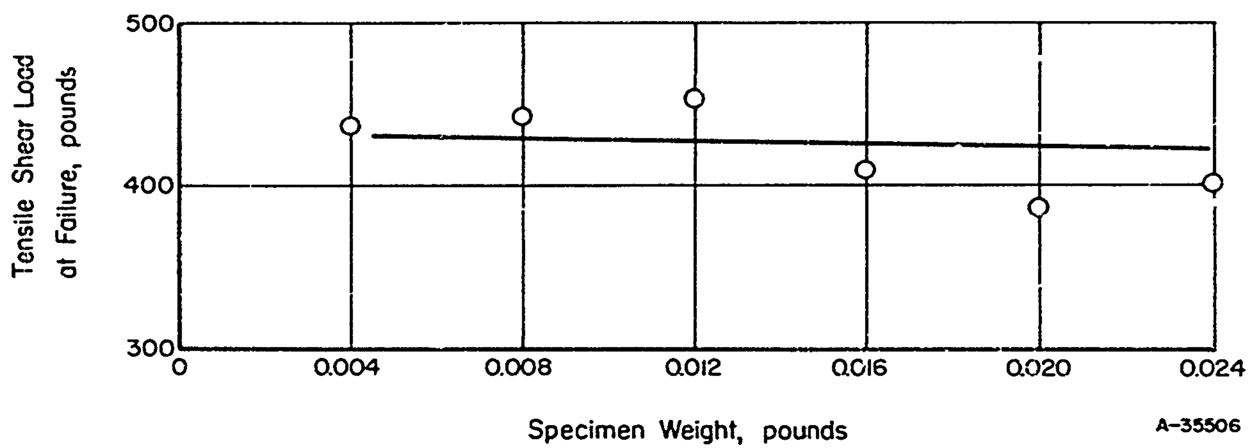


FIGURE 13. EFFECT OF MASS ON TENSILE SHEAR STRENGTH IN 0.04-INCH-THICK 1100-H18 ALUMINUM

Weldability of 1100 aluminum did not appear to be affected by sheet mass or in making multiple spot welds, so it is anticipated that structures of different sizes and shape could be welded.

Cracks at the edges of many welds were observed in metallographic examinations. Attempts to eliminate the cracks by welding in vacuum with and without preheat were not successful. Welds made in vacuum tended to have fewer cracks than those made in air, but the quality of the bonds made in vacuum was poorer than that of welds made in air. It is believed that the differences obtained in welds in air and vacuum were primarily due to the differences in shear force or coefficient of friction. The coefficient of friction of materials in vacuum is considerably higher than that in air so that the tip displacements obtained in air would be higher than those in vacuum. It is believed that making a weld of good quality require higher energies in vacuum than in air.

WELDING OF HEAT-RESISTANT ALLOYS

One of the most attractive applications for the ultrasonic welding process is its possible use in welding similar and dissimilar material combinations which cannot be welded satisfactorily by other processes. In this program, attempts were made to obtain satisfactory ultrasonic welds in several material combinations. The material combinations studied were:

C-110M titanium to C-110M titanium

C-110M titanium to AISI Type 316 stainless steel

AISI Type 316 stainless steel to AISI Type 316 stainless steel

Niobium to niobium

Niobium to AISI Type 316 stainless steel

Inconel to Inconel

Mo-0.5Ti to Mo-0.5Ti

All of the welds were evaluated on the basis of tensile shear tests and metallographic examinations.

Ultrasonic welds were made in annealed 0.025-inch-thick C-110M titanium, in 0.018-inch-thick AISI Type 316 stainless steel, and between C-110M titanium and Type 316 stainless steel. The welding tip was 4-inch-spherical-radius Monel (Type 7) and the anvil was mild steel coated with a hard-facing alloy. Approximate power input to the transducer was 2.2 kw. The specimens were clamped to the anvil during welding. In welding C-110M titanium, tip sticking generally was not a problem; however, the welding tip stuck frequently when welding Type 316 stainless steel.

Shear strength of these welds is shown in Table 9. The data show that the shear strength of welds in C-110M titanium and in Type 316 stainless steel were high and consistent. The strength of welds between C-110M titanium and 316 stainless steel were low compared with the strength of joints in the metals welded to themselves.

TABLE 9. TENSILE SHEAR STRENGTHS OF ULTRASONIC WELDS IN 0.025-INCH C-110M TITANIUM AND IN 0.018-INCH AISI TYPE 316 STAINLESS STEEL

		C-110M Titanium		C-110M Titanium to AISI Type 316 Stainless Steel		AISI 316 Stainless Steel	
Clamping Force, pounds	Welding Time, seconds	Shear Strength, pounds	Type of Failure(a)	Shear Strength, pounds	Type of Failure(a)	Shear Strength, pounds	Type of Failure(a)
200	0.5	600	Shear	330	Shear	430	POB
200	1.0	510	Shear	305	Shear	475	POB
200	1.5	555	Shear	300	Shear	485	POB
250	0.5	605	Shear	365	Shear	425	Shear
250	1.0	625	Shear	330	Shear	525	POB
250	1.5	615	POB	285	Shear	430	Base metal
300	0.5	465	POB	385	Shear	395	Shear
300	1.0	575	POB	335	Shear	570	POB
300	1.5	550	POB	270	Shear	475	POB

(a) POB = pulled-out button.
Base metal = fracture occurred at edge of nugget.

Several observations were made during metallographic examinations of these welds. It was found that cracking occurred in welds in titanium at the edge of nugget when welding times were 1.5 seconds but did not occur when welding times were 0.5 and 1 second. Cracking occurred in all of the welds in Type 316 stainless steel and between C-110M titanium and Type 316 stainless steel. However, the cracking observed in these welds was along

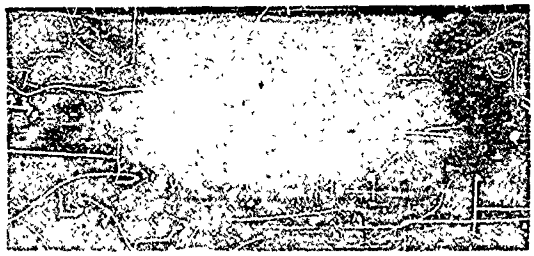
the bond line rather than in the base metal at the edge of the nugget. Metallographic studies showed that the titanium welds were heated into the beta field during welding. Figure 14 shows weld zones in titanium welds for several welding times. It can be seen that the size of the weld zone increased with weld time. It appears that the heat was generated at the tip-titanium and the titanium-titanium interfaces. The temperature at the interfaces must be high since the weld zone has been heated above the beta transus, which is about 1400 F for C-110M. The beta structure obtained in the weld zone consists of rectangular-shaped grains (Figure 15). Structures with grains of this shape are not normally found in this alloy, even when the alloy is severely quenched. It may be that the rectangular structure is due to straining from the ultrasonic motion. Similar structures in ultrasonic welds in this alloy and several other materials also have been observed by others.[9]

A photomicrograph at 30X of a weld between C-110M titanium and AISI 316 stainless steel is shown in Figure 16. Here again, it can be seen that the titanium was heated above the beta transus (1400 F). An area of the joint is shown at 500X also in Figure 16. It can be seen that alloying occurred between the stainless steel and titanium. The interface consists of two phases, probably a beta matrix and patches of an alloy compound. The alloy or reaction zone at the interface was not identified, but nickel and titanium form a eutectic at about 1800 F and iron forms a eutectic with titanium at 2000 F, so the alloy is probably the result of one or both of these eutectics. The hardness of the interface or reaction zone is indicated on Figure 16.

In all of the welds between titanium and stainless steel, cracks were observed along the bond line. These cracks were always present between the titanium and the interface alloy. The cracking and high hardness of the interface probably account for the low shear strength obtained in these joints.

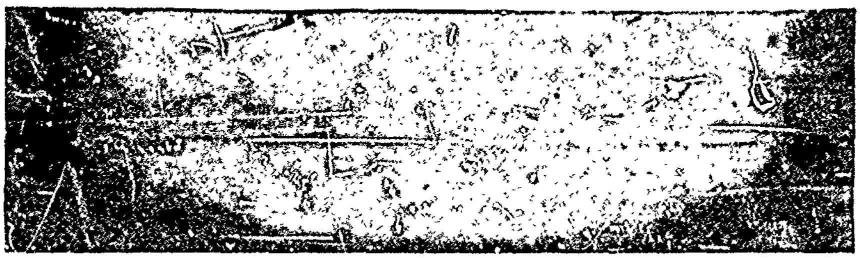
Niobium and AISI Stainless Steel

Ultrasonic welds were made in 0.015-inch-thick niobium and between 0.015-inch-thick niobium and 0.018-inch-thick AISI Type 316 stainless steel. The welds were made by the procedures described in the last section on titanium. One difficulty found in welding niobium was that excessive tip sticking occurred. The shear strengths of the welds are given in Table 10. The data show that the strength of the welds made with three different clamping pressures and three different welding times were comparable. In addition, the strength of the welds made between niobium and Type 316 stainless steel was comparable with that of welds made in niobium. In the niobium-stainless steel joints, all of the welds failed by pulling a nugget in the niobium.



Welding Time: 0.5 second

Welding Time: 1 second

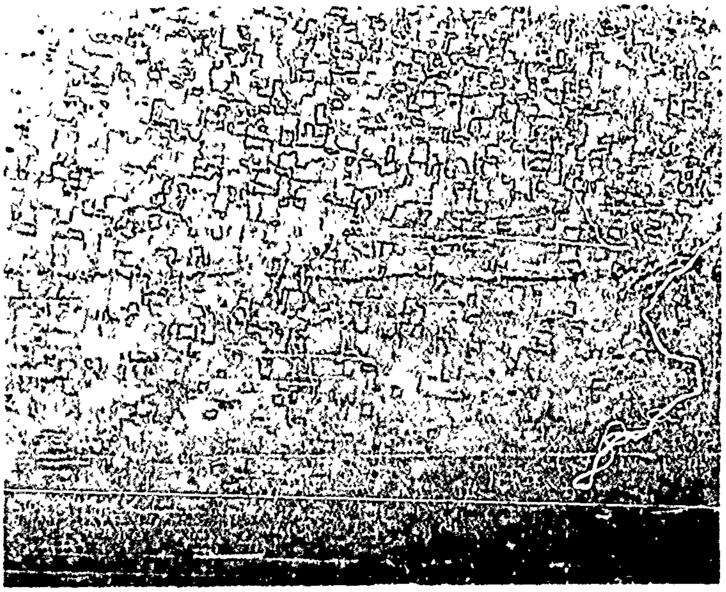


Welding Time: 1.5 seconds

30X Etchant: 30 Lactic, 30 HNO_3, 1 HF N67780

FIGURE 14. CROSS SECTIONS OF ULTRASONIC WELDS IN C-110M TITANIUM

Clamping force: 250 pounds
Power to transducer: approximately 2.2 kw.



100X Etchant: 30 Lactic, 30 HNO_3, 1 HF N67776

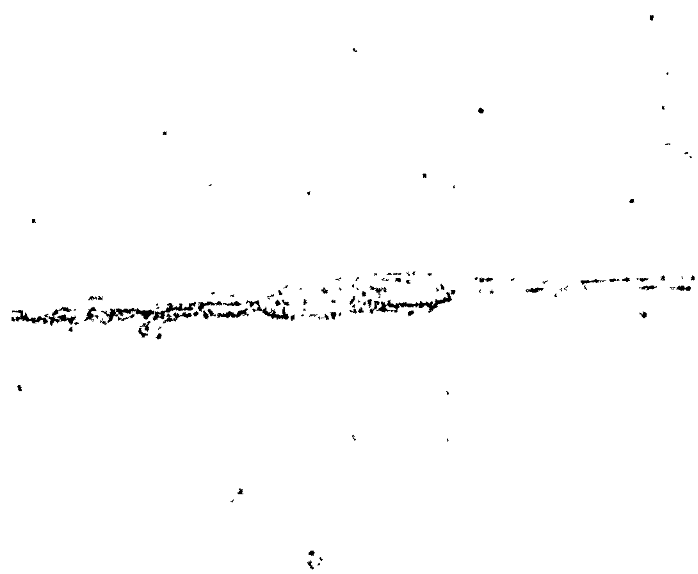
FIGURE 15. WELD-ZONE STRUCTURE OBTAINED IN C-110M TITANIUM WELDS

Welding time:	1 second
Clamping force:	250 pounds
Power to transducer:	approximately 2.2 kw.

Type 316 stainless steel

C-110M titanium

30X Etchant: 30 Lactic, 10 HNO_3, 1 HF N67782



Type 316 stainless steel

Reaction zone, 720 KHN

C-110M titanium-461 KHN

500X Etchant: 30 Lactic, 10 HNO_3, 1 HF N67778

FIGURE 16. ULTRASONIC WELDS BETWEEN AISI TYPE 316 STAINLESS STEEL AND C-110M TITANIUM

Welding time:	1.5 seconds
Clamping force:	250 pounds
Power to transducer:	approximately 2.2 kw.

TABLE 10. TENSILE SHEAR STRENGTHS OF ULTRASONIC WELDS IN NIOBIUM AND BETWEEN 0.015-INCH NIOBIUM AND 0.018-INCH AISI TYPE 316 STAINLESS STEEL

		Niobium		Niobium to AISI Type 316 Stainless Steel	
Clamping Force, pounds	Welding Time, seconds	Shear Strength, pounds	Type of Failure[a]	Shear Strength, pounds	Type of Failure[a]
200	0.5	165	Shear	220	POB
200	1.0	160	POB	190	POB
200	1.5	155	POB	170	POB
250	0.5	180	Shear	190	POB
250	1.0	195	POB	205	POB
250	1.5	160	Shear	195	POB
300	0.5	190	POB	210	POB
300	1.0	205	POB	185	POB
300	1.5	175	Shear	200	POB

(a) POB = pulled-out button.

30X Etchant: 30 Lactic, 10 HNO_3, 1 HF N67783

FIGURE 17. ULTRASONIC WELD BETWEEN 0.015-INCH-THICK NIOBIUM AND 0.018-INCH-THICK AISI TYPE 316 STAINLESS STEEL

Welding time: 1 second
Clamping force: 250 pounds
Power to transducer: approximately 2.2 kw.

Metallographic studies of the joints showed that good bonds were obtained, but cracking was observed in the niobium in all of the joints. Figure 17, a photomicrograph of joint between niobium and stainless steel, exemplifies the cracking that occurred in welding niobium.

Inconel

Ultrasonic welds were made in 0.018-inch-thick Inconel with a 4-inch-spherical-radius Monel tip and a mild-steel anvil coated with a hard-facing alloy. The specimens were clamped to the anvil during welding. Estimated power input to the transducer was 2.2 kw. No difficulties were found in making the welds except that excessive tip sticking occurred.

Shear strengths of the welds are shown in Table 11. The strengths of welds in Inconel are high and are comparable with those obtained in resistance spot welding. However, metallographic examinations of the welds showed cracks at the edge of the nugget in all of the welds. The cracks were similar to those obtained in welding 17-7PH stainless steel.

TABLE 11. TENSILE SHEAR STRENGTHS OF ULTRASONIC WELDS IN 0.018-INCH-THICK INCONEL

Clamping Force, pounds	Welding Time, seconds	0.018-Inch-Thick Inconel Shear Strength, pounds	Type of Failure[a]
200	0.5	280	POB
200	1.0	390	POB
200	1.5	435	POB
250	0.5	410	Shear
250	1.0	490	Base metal
250	1.5	460	POB
300	0.5	460	POB
300	1.0	470	POB
300	1.5	535	POB

(a) POB = pulled-out button.
Base metal = failure occurred at edge of nugget.

Molybdenum

Attempts were made to ultrasonically weld 0.005-, 0.010-, and 0.015-inch-thick Mo-0.5Ti alloy. A Type 7 welding tip and a mild-steel

anvil were used. The specimens were clamped to the anvil during welding. Clamping force was 100 pounds to 300 pounds, welding time was 0.5 to 6 seconds, and approximate power to transducer was 1 kw to 2.2 kw. Welds with satisfactory shear strengths were not obtained under any of the conditions. The strength of the welds ranged from 25 to 80 pounds. The low weld strengths were believed due to insufficient energy at the weld site, since the coefficient of friction of molybdenum against molybdenum is greater than that of molybdenum against Monel. In welding molybdenum, severe tip sticking occurred, indicating that most of the ultrasonic energy was dissipated at the tip-specimen interface instead of the weld site. Also, the faying surfaces at the weld site were polished; bonds about 1/16 inch in diameter generally occurred randomly at two or three spots within the polished surfaces, also indicating that insufficient energy was obtained at the weld site. Attempts were made to relieve this situation by changing the tip material. This was done by brazing various materials, such as molybdenum, titanium, and stainless steel, to the Monel tip. However, it was found that considerable energy was lost at the braze interface and ultrasonic energy was not effectively transferred to the joint interface.

In work done at Westinghouse on ultrasonic welding(10) of the Mo-0.5Ti alloy (0.015 inch thick), weld shear strengths over 300 pounds were obtained when using a power input to the transducers of 5.2 kw. The machine used in this work had four transducers, two driving the upper tip and two driving a lower tip. The other welding conditions were similar to those used in this study (clamping force of 300 pounds and weld time of 3 to 5 seconds). Apparently, higher power inputs than the 2.2 kw in the available equipment are needed to obtain welds in molybdenum. Aeroprojects also has reported(11) shear strengths of 240 pounds (0.015-inch-thick material) and 330 pounds (0.020-inch-thick material) for welds in arc-cast molybdenum. However, in work conducted for Boeing Airplane Company, it was reported(12) that preliminary welding studies were not considered successful enough to warrant preparation of strength test specimens.

The variation in results obtained in attempts to weld molybdenum or the Mo-0.5Ti alloy seems to indicate that welding conditions are extremely critical or that process control is not developed sufficiently to provide reproducible results.

Discussion of Welding Heat-Resistant Alloys

The major difficulty observed in welding the heat-resistant alloys was cracking. In welding titanium (C-110M), the initiation of cracks appeared to be a function of time. Welds made with weld times of 0.5 and 1 second were crack free. However, welds made at 1.5 seconds contained cracks. Welds made in all of the other materials, AISI Type 316 stainless steel, Inconel, niobium, and 17-7PH stainless steel, also contained cracks. The

cracks observed in the welds made in these materials were similar except those in AISI 316 stainless steel were observed along the bond line rather than in the base metal at the edge of the nugget. Cracks of this type also were observed in welds between C-110M titanium and AISI 316 stainless steel. However, in these welds, alloying occurred between the titanium and stainless steel. The hardness of the interface or alloyed zone was very high compared with the hardness of the base materials. It is possible that the cracking observed in these welds was caused by the hard and apparently brittle reaction zone at the interface.

In welds made in C-110M titanium and 17-7PH stainless steel, it was found that the weld zone was heated to high temperatures. It is estimated that the temperatures reached in the weld zone were between 1500 and 2000 F. However, the temperature reached at the weld interface would be expected to be much higher than 2000 F since the heat is generated at the interface. It is conceivable from these data that the weld interface is heated to, or near, the melting point of the material being welded.

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